Increasing the detectability of a buried object by depositing a passive superstrate on the ground

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Abstract: A ground-penetrating radar (GPR) antenna excites a perfectly electric conducting (PEC) inclusion buried inside the ground. One of the main problems in the detection of the PEC inclusion via external measurements is its poor scattering response due to attenuation. Hence, increasing the scattered power generated by the inclusion is of great practical interest. To this direction, the main purpose of this work is to investigate a procedure of unlocking the ground by depositing a thin passive layer of conventional material atop of it. The first step of the developed methodology is to significantly enhance the transmission into a lossy half space, in the absence of the inclusion, by covering it with a passive slab, the thickness and permittivity of which are to be determined. Then, the full boundary value problem (including the inclusion) is solved semi-analytically via integral equations techniques. The scattered power of the buried inclusion is compared to the corresponding quantity when no additional layer is present. Results from numerical simulations are presented exhibiting the effectiveness of the approach. Substantial improvement in the detectability of the inclusion is reported for several types of ground and burying depths by using conventional realizable passive materials. The effects of the shape of the buried inclusion on the scattered field are also investigated. The developed technique may constitute an effective configuration (structural) preprocessing which may be used as an initial step in the analysis of related problems before the application of an inverse scattering algorithm concerning the efficient processing of the scattering data.

Keywords: Buried inclusion, GPR methodologies, detectability, integral equations, inverse scattering, mixing formulas.

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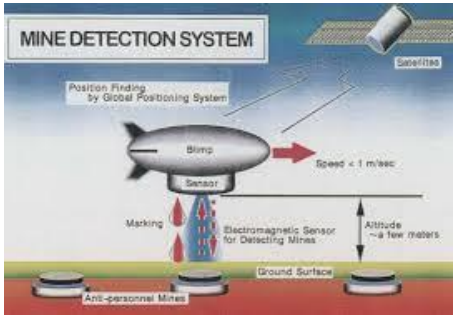
Outline

- Detection of buried objects inside the earth:
  - motivation
  - background on GPR methods
- Buried inclusion configuration – research purpose
- Semi-analytic solution of the boundary value problem:
  - analysis of the homogeneous (inclusion-free) structure
  - integral equation computation of the unknown current on the inclusion
- Increasing the detectability of the inclusion: adopted strategy
- Numerical results
- Conclusions

Detection of buried objects inside the earth

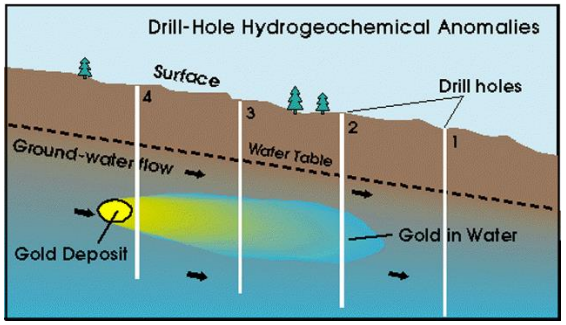
- Mines

  Dubey, Barnard (Eds.),
  Proc. SPIE 1997
  Bourgeois, Smith,
  IEEE TAP 1998



- Mineral deposits

  Constable, Srnka,
  Geophysics 2007
  Khan, Jacobson,
  Geol. Soc. Am. Bulletin 2008

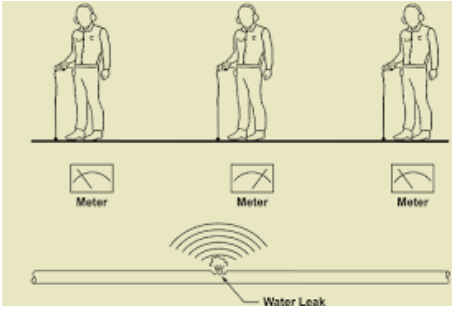


- Unexploded ordnances (UXOs)

  Huang, Won, *Geophysics* 2003
  Huang, SanFilipo, Oren, Won,
  J. Applied Geophysics 2007

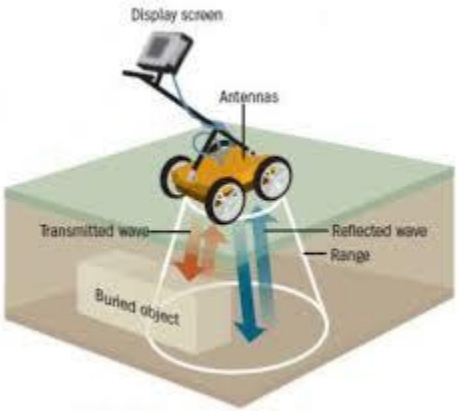
- Buried pipes

  Peters, Daniels, Young,
  Proc. IEEE 1994
  Liu, Shen,
  IEEE Trans. Geosci. Rem. Sens. 1991



Background on GPR methods

- Localization and reconstruction of buried objects: various methods
- Characteristic representatives are methods with primary fields generated by ground-penetrating radars (GPRs):
  - waves from a moving radar, lying close to the ground, record the strength of the (near-field) echo produced by the interaction with the buried objects received at the air-soil interface in a multi-static configuration.



Daniels, *IEE Press*, 1996

Crocco, Soldovieri, *Annals of Geophysics* 2003

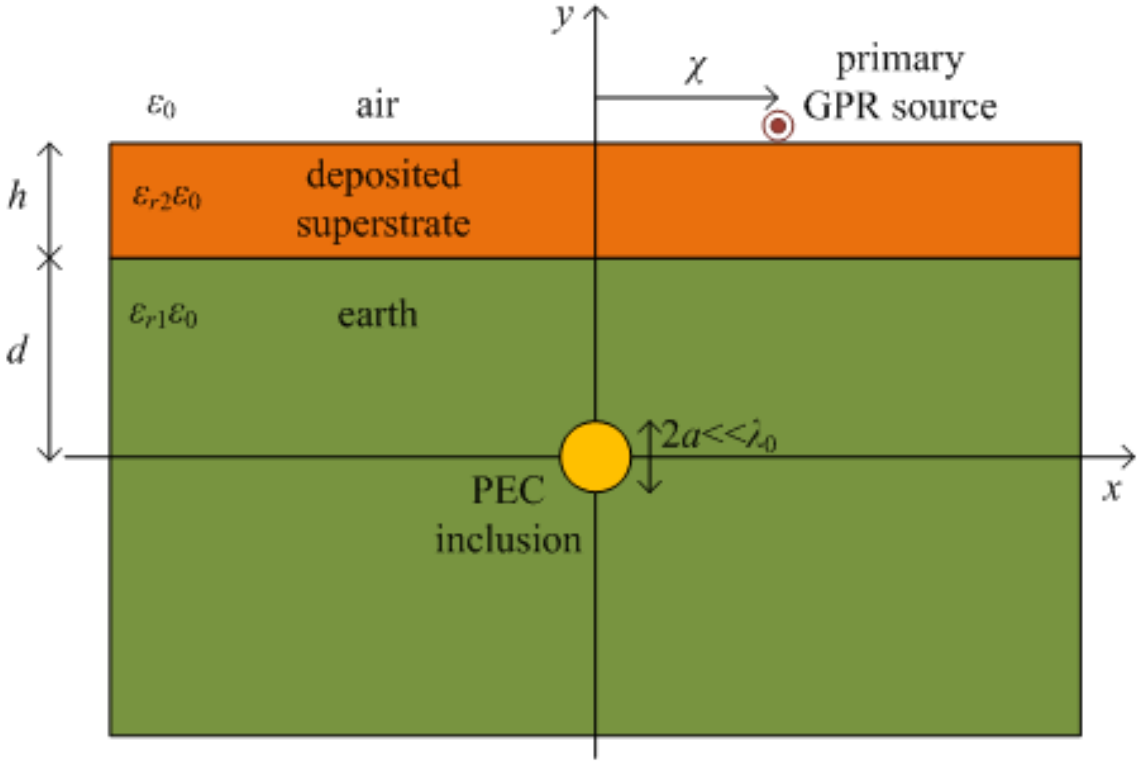
- Important characteristics: number of utilized frequencies and type of the primary field (pulse or harmonic wave)

  Cui et al., *IEEE Trans. Geosc. Rem. Sens.* 2003

  Song et al., *IEEE Trans. Antennas Propagat.* 2005

  Pasolli, Melgani, Donelli, *IEEE Trans. Geosc. Rem. Sens.* 2009

A different approach
Configuration – research purpose



- Deposit on the lossy earth a suitable thin, reciprocal and *passive* superstrate layer assisting the primary field's penetration in the earth as well as the buried obstacle's scattering response in the air.
- Main objective: *determine characteristics of this layer such that the detectability of a buried PEC inclusion is increased.*

Semi-analytic solution of the BVP[1]

Induced fields in the homogeneous structure due to the GPR primary field

- Primary GPR field, due to a line source located in free space;
  the *z*-component of its electric field is given by the Fourier integral

$$E_{0,inc}(x,y) = -\frac{jIk_0\zeta_0}{4\pi}\int_{-\infty}^{+\infty}\frac{e^{-g_0(\beta)|y-d-h|}}{g_0(\beta)}e^{-j\beta(x-\chi)}d\beta$$

- *Background* electric field transmitted in the earth region
  (in the absence of the PEC inclusion)

$$E_{1,back}(x,y) = \int_{-\infty}^{+\infty}\gamma_{back}(\beta)e^{g_1(\beta)y}e^{-j\beta(x-\chi)}d\beta,$$

$$\gamma_{back}(\beta) = \frac{jIk_0\zeta_0}{\pi}\frac{g_2(\beta)e^{-g_1(\beta)d}}{e^{-g_2(\beta)h}(g_2(\beta)-g_0(\beta))(g_2(\beta)-g_1(\beta)) - e^{g_2(\beta)h}(g_2(\beta)+g_0(\beta))(g_2(\beta)+g_1(\beta))}$$

$$g_0(\beta) = \sqrt{\beta^2 - k_0^2} \qquad g_1(\beta) = \sqrt{\beta^2 - k_0^2\epsilon_{r1}} \qquad g_2(\beta) = \sqrt{\beta^2 - k_0^2\epsilon_{r2}}$$

Semi-analytic solution of the BVP[2]

Green's function of the homogeneous structure

- The homogeneous (inclusion-free) structure is excited by a 2-D line source, lying in the earth.
- Expression of the Green's function:
  - in the earth region

$$G_1(x,y,X,Y) = G_1^{pr}(x,y,X,Y) + G_1^{sec}(x,y,X,Y)$$

$$= -\frac{j}{4}H_0^{(2)}\left(k_0\sqrt{(x-X)^2+(y-Y)^2}\right) + \int_{-\infty}^{+\infty}\gamma_1^{sec}(\beta)e^{g_1(\beta)(y+Y)}e^{-j\beta(x-X)}d\beta,$$

$$\gamma_1^{sec}(\beta) = \frac{e^{-2g_1(\beta)d}}{4\pi g_1(\beta)}\frac{\cosh(g_2(\beta)h)(g_1(\beta)-g_0(\beta))g_2(\beta)+(g_0(\beta)g_1(\beta)-g_2^2(\beta))\sinh(g_2(\beta)h)}{\cosh(g_2(\beta)h)(g_1(\beta)+g_0(\beta))g_2(\beta)+(g_0(\beta)g_1(\beta)+g_2^2(\beta))\sinh(g_2(\beta)h)}$$

  - in the air region

$$G_0(x,y,X,Y) = \int_{-\infty}^{+\infty}\gamma_0(\beta)e^{-g_0(\beta)(y-Y)}e^{-j\beta(x-X)}d\beta,$$

$$\gamma_0(\beta) = \frac{1}{\pi g_0(\beta)}\frac{e^{g_0(\beta)(d+h)-g_1(\beta)d}g_0(\beta)g_2(\beta)}{e^{g_2(\beta)h}(g_0(\beta)+g_2(\beta))(g_1(\beta)+g_2(\beta))-e^{-g_2(\beta)h}(g_0(\beta)-g_2(\beta))(g_1(\beta)-g_2(\beta))}$$

Semi-analytic solution of the BVP[3]

Integral representation of the scattered field

- Integral representation of the scattered field in the earth

$$E_{1,sc}(x,y) = -jk_0\zeta_0 \int_C K(l) \left[\begin{array}{c} G_1^{pr}(x,y,X(l),Y(l)) \\ +G_1^{sec}(x,y,X(l),Y(l)) \end{array} \right] dl$$

$K(\ell)$: surface current induced on the boundary C of the PEC inclusion

- Thin-wire approximation (due to the small electrical size of the cylinder): the (unknown) current K does not vary significantly around C and, therefore, we may consider it as spatially constant.

- In this way, the scattered field at the origin is approximated by

$$E_{1,sc}(0,0) \cong -\frac{\pi k_0 a \zeta_0 K}{2} H_0^{(2)}(k_0 a\sqrt{\epsilon_{r1}}) - 2\pi j k_0 a \zeta_0 K G_1^{sec}(0,0,0,0)$$

Semi-analytic solution of the BVP[4]

Boundary condition and current's computation

- Imposing the PEC boundary condition at the center of the PEC cylinder:

$$E_{1,back}(0,0) + E_{1,sc}(0,0) = 0$$

- yields the unknown current:

$$K = \frac{j}{2\pi k_0 a \zeta_0} \frac{E_{1,back}(0,0)}{\frac{j}{4} H_0^{(2)}(k_0 a \sqrt{\epsilon_{r1}}) - G_1^{sec}(0,0,0,0)}$$

- Approximation of the scattered field in the air region:

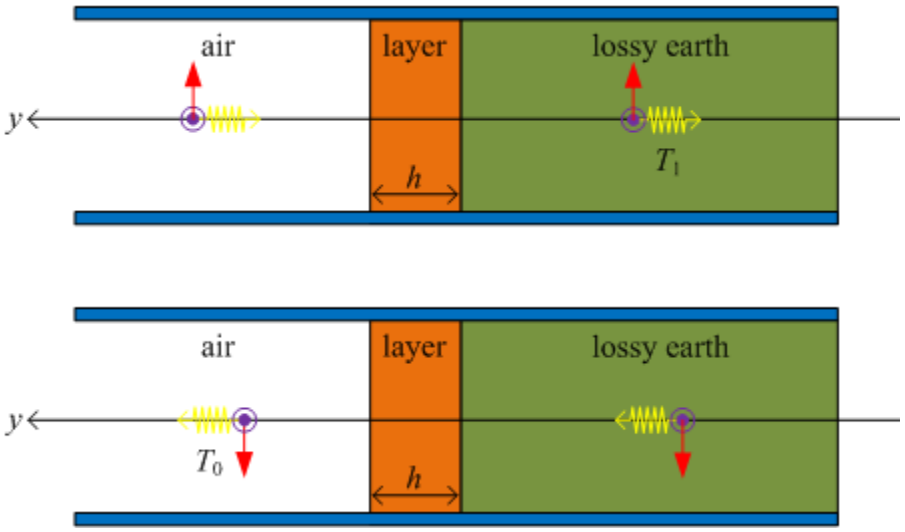
$$E_{0,sc}(x,y) \cong -2\pi j k_0 a \zeta_0 K G_0(x,y,0,0) = -2\pi j k_0 a \zeta_0 K \int_{-\infty}^{+\infty} \gamma_0(\beta) e^{-g_0(\beta) y - j\beta x} d\beta$$

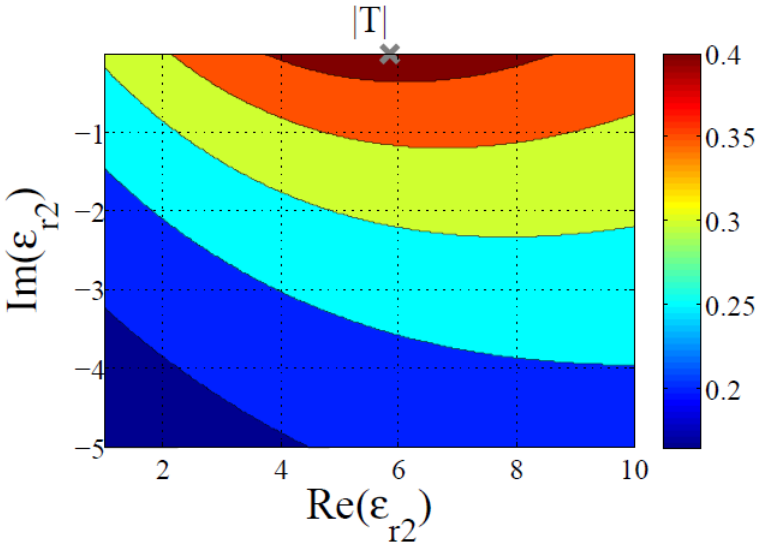
- Scattered far-field power in the upper half-space (stationary phase approximation):

$$P_{sc} = 8\pi^4 (k_0 a)^2 k_0 \zeta_0 |K|^2 \int_0^{\pi} |\gamma_0(k_0 \cos\phi)|^2 \sin^2\phi \, d\phi$$

Adopted strategy[1]: the inclusion-free problem

- Examination of two simplified scattering problems corresponding to the inclusion-free configuration under normal plane wave incidence





max|*T*| : lossless superstrate

$$\frac{T_0}{\sqrt{\epsilon_{r1}}} = T_1 e^{-jk_0 h}$$

$$= \frac{4\sqrt{\epsilon_{r2}}}{e^{jk_0 h\sqrt{\epsilon_{r2}}}\left(1+\sqrt{\epsilon_{r2}}\right)\left(\sqrt{\epsilon_{r1}}+\sqrt{\epsilon_{r2}}\right) - e^{-jk_0 h\sqrt{\epsilon_{r2}}}\left(1-\sqrt{\epsilon_{r2}}\right)\left(\sqrt{\epsilon_{r1}}-\sqrt{\epsilon_{r2}}\right)} \equiv T$$

- max|*T*|= max|T_0|, max|T_1|:

  max power transmitted to the earth and simultaneously returned to air

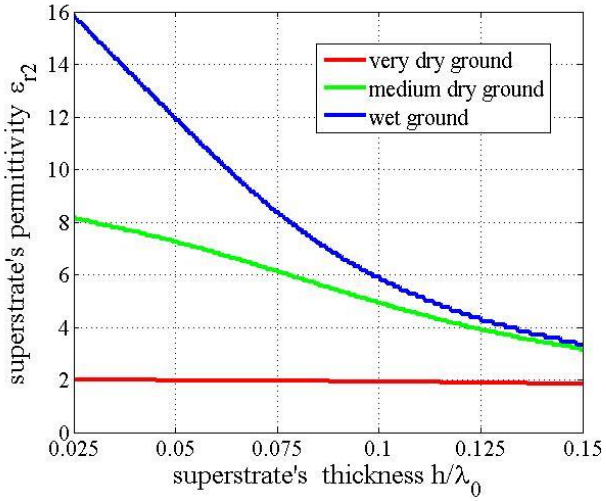
Adopted strategy[2]: the inclusion problem

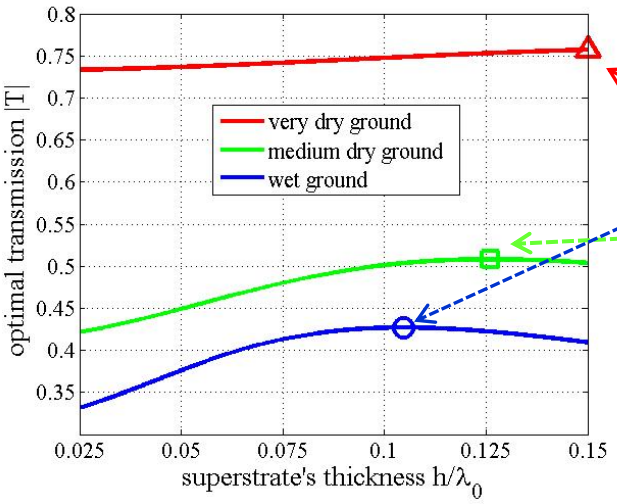
- Max |*T*| (in the inclusion-free) problem: *candidate optimal points*
- Test these points in the actual/physical configuration where the obstacle is present and the primary field is due to a moving GPR source.
- Criterion for determining the optimal values of *h* and ε_{r2} such that the detection of the inclusion's location becomes more feasible

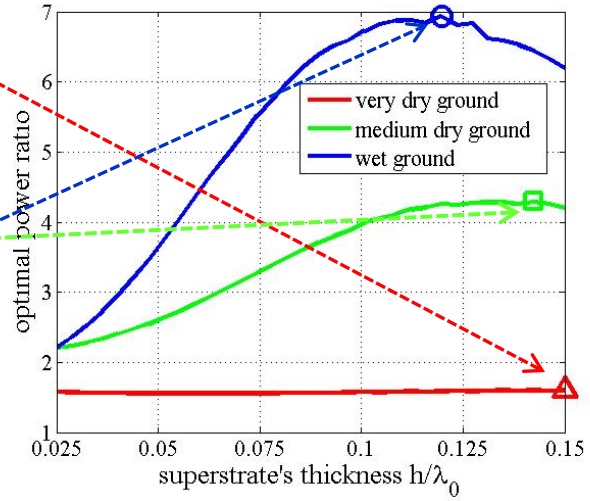
$$\max\left\{\frac{P}{\tilde{P}}\right\} = \max\left\{\frac{\int_{-\infty}^{+\infty} P_{sc}(\chi)d\chi}{\int_{-\infty}^{+\infty} \tilde{P}_{sc}(\chi)d\chi}\right\}$$

← with superstrate

← no superstrate





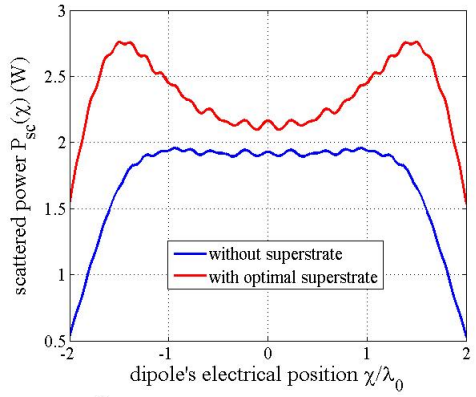


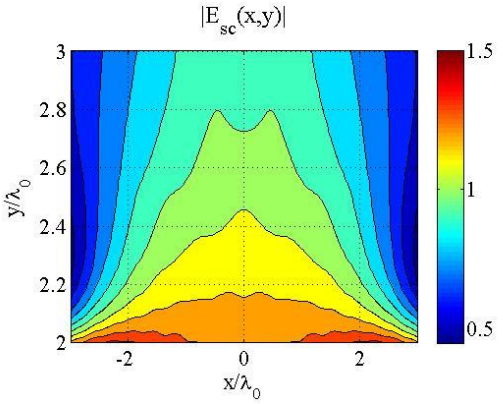
optimal points of the inclusion problem are very close to the inclusion-free one

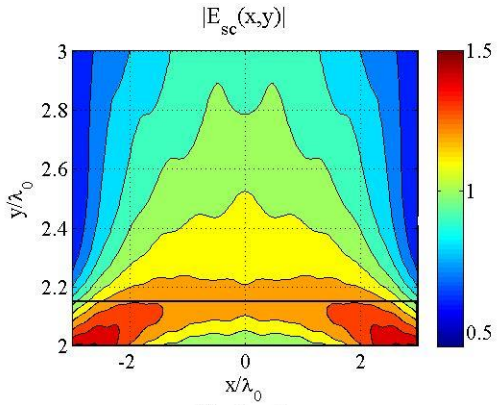
Optimal superstrates increasing the inclusion's detectability

without superstrate

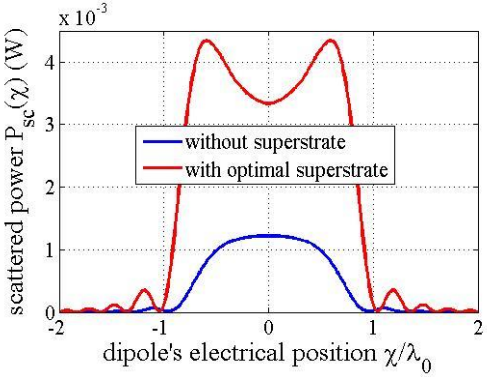
with optimal superstrate

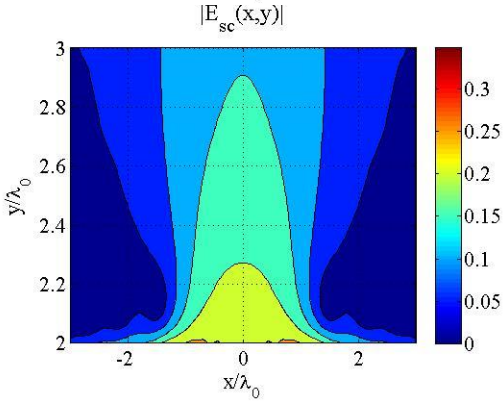


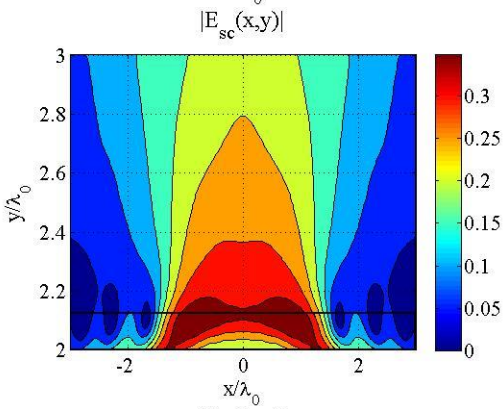




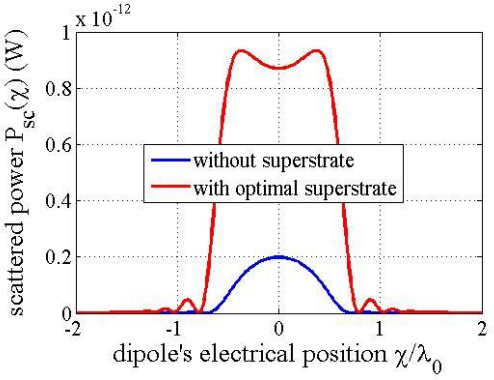
very dry ground

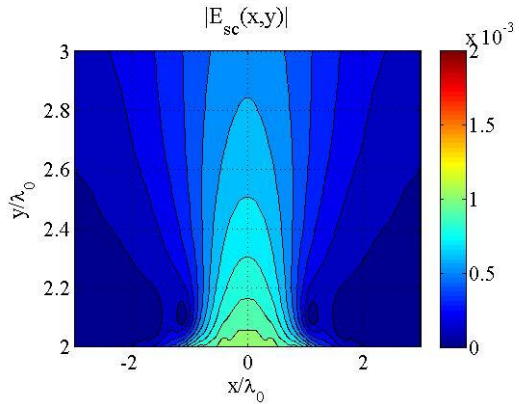


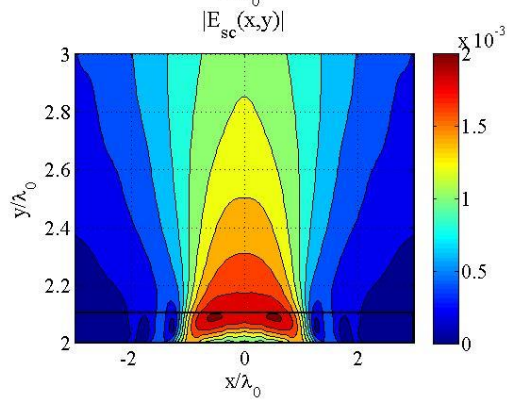




medium dry ground



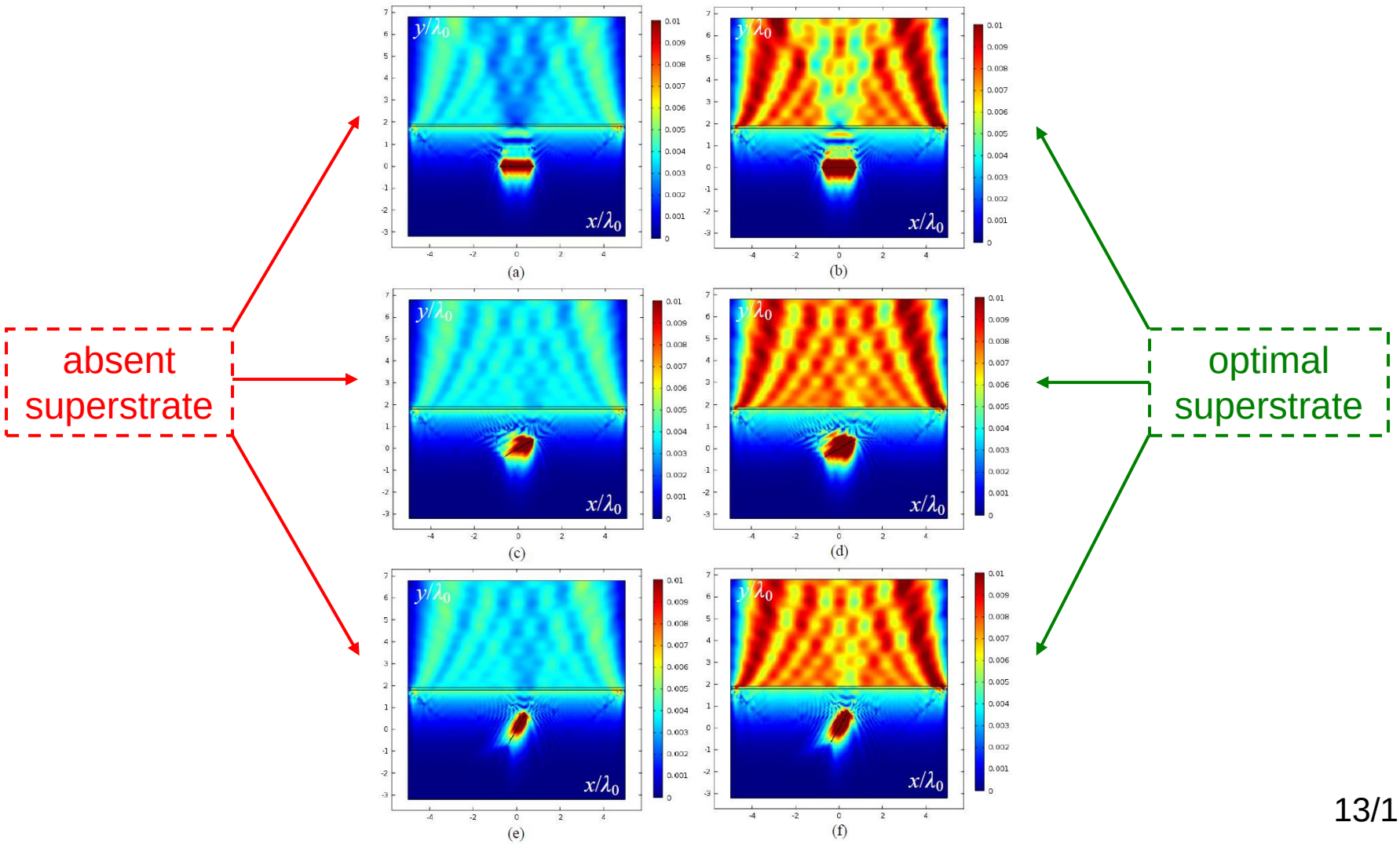




wet ground

Scattered field's amplification for different inclusions[1]

- PEC strip of width $1.5\lambda_0$ and different inclination angle buried at $d=1.8\lambda_0$ (wet ground @ 750MHz)
- Scattered field simulations are performed with COMSOL Multiphysics

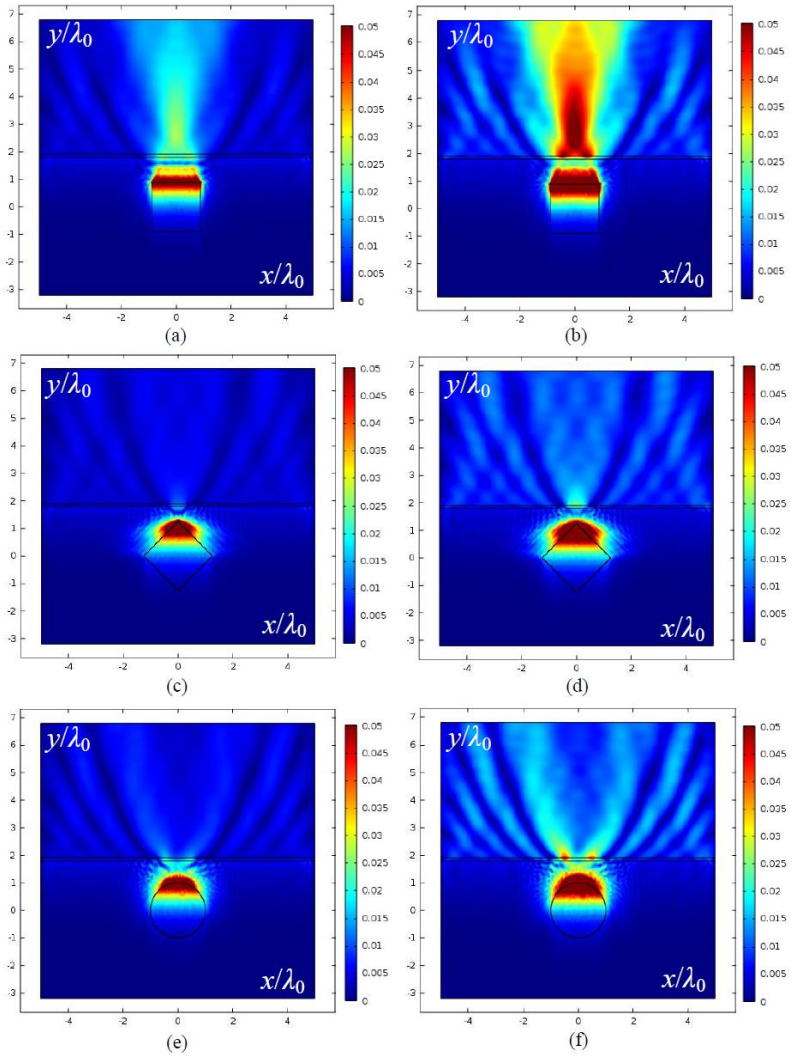


Scattered field's amplification for different inclusions[2]

- PEC square, rhombus, circle (all of the same area with $a=\lambda_0$) buried at $d=1.8\lambda_0$ (wet ground @ 750MHz)
- Scattered field simulations are performed with COMSOL Multiphysics

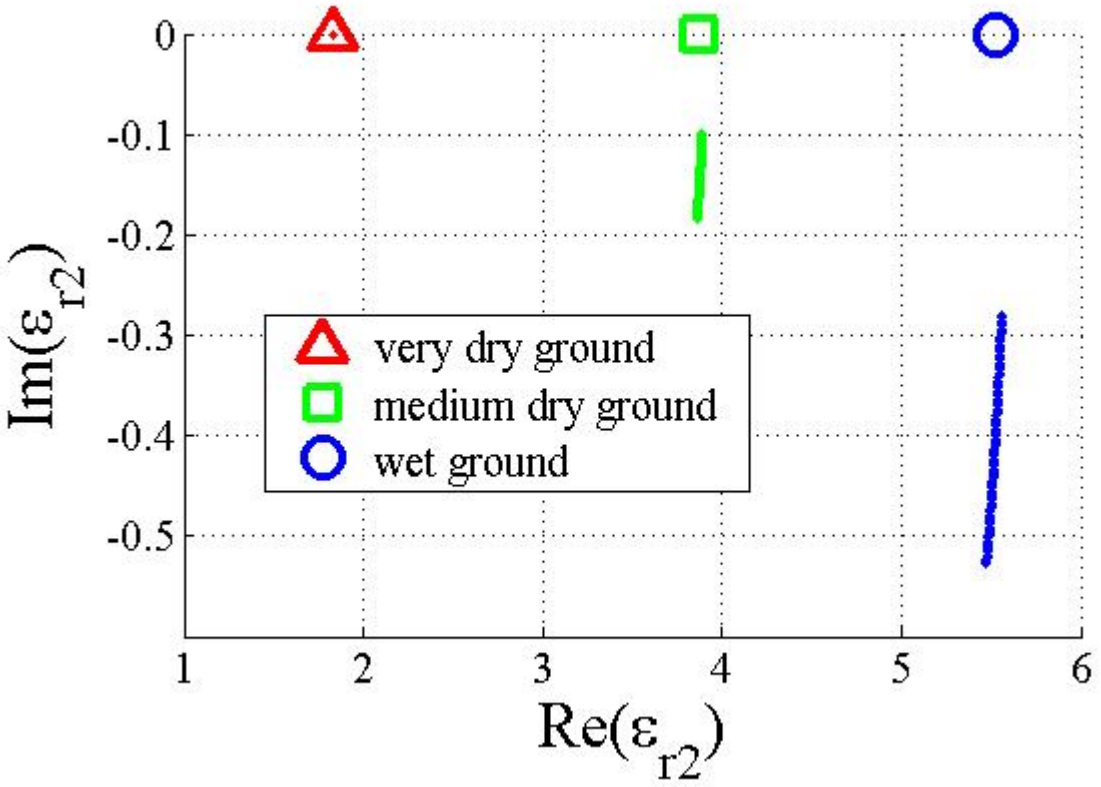
absent superstrate

optimal superstrate



Realizing the optimal parameters by mixtures of ordinary materials

- Realizable permittivities (mixture of sand and foam disks and mixture of sand and propanol = propanol-soaked sand) compared to the optimal ones determined by the developed methodology



Conclusions

- Motivations for the detection of buried objects and related GPR methodologies
- Research objective: increasing the detectability of a buried PEC inclusion by depositing atop the earth a suitable superstrate layer.
- The boundary value problem is solved by a semi-analytic integral equation methodology.
- Numerical results: optimal values of the superstrate's parameters achieving the objective for different excitations and inclusion's shapes
- The resulting optimal values may be well approximated by mixtures of ordinary materials.

for more details

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"Unlocking" the Ground: Increasing the Detectability of Buried Objects by Depositing Passive Superstrates

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